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III-V COMPOUND SEMICONDUCTOR NATIVE OXIDE MOSFETs WITH FOCUS ON INTERFACE STUDIES

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FINAL REPORT

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July 2001

ABSTRACT

The application of Al-bearing III-V compound semiconductor native oxides for GaAs-based metal oxide semiconductor (MOS) electronic devices has been explored. An insulated-gate buried-channel high-electron-mobility transistor (HEMT) using an AlGaAs native oxide and modulation-doped InGaAs channel has been demonstrated. InAlP native oxides have been shown to have superior electrical properties compared to those of AlGaAs, with insulating quality comparable to that of SiO_2 on Si. We have demonstrated the formation of an inversion layer in heterostructure MOS capacitors employing an InAlP native oxide gate insulator. Transmission electron microscopy has been used to examine the oxide/semiconductor interface region. The use of a thin InGaP oxidation barrier layer is shown to improve native oxide uniformity and electrical quality. The InAlP oxide is found to be sufficiently dense to cap and suppress the oxidation of GaAs. X-ray absorption fine-structure spectroscopy (XAFS) and x-ray reflectivity techniques were applied to III-V native oxides using a beamline at the Argonne National Laboratory Advanced Photon Source. Residual As atoms in oxidized AlGaAs films have been found to be coordinated with oxygen in the form of amorphous As oxides. The density profiles of thin surface-oxidized AlGaAs films are obtained by applying a model-independent fitting method to x-ray reflectivity data.

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1. Introduction

Wet-thermal native oxides of III-V compound semiconductors, discovered at the University of Illinois in 1990 [1], have had a revolutionary impact on optoelectronics. The most technologically important thus far is the oxide of AlGaAs, now widely used in vertical cavity surface-emitting lasers (VCSELs) for current isolation. The potential for achieving a suitable electronic-quality oxide in the GaAs material system akin to SiO_2 on Si has yet to be realized. In addition to several demonstrations of AlGaAs native oxide MOSFETs [2-4], several other studies [5-11] have evaluated this oxide's potential for electronic applications. An InP-based InAlAs native oxide MOSFET has also been reported [12]. Past explorations of native oxides have failed to produce an adequate insulator possessing low leakage currents, high breakdown fields, and low interface trap densities as required for metal-oxide-semiconductor (MOS) device applications. Native oxides formed via wet thermal oxidation of AlGaAs have thus far shown unacceptably high leakage currents and Fermi-level pinning due to residual As [5, 9]. It has become apparent that residual interfacial As produced during the oxidation of III-As materials creates midgap traps [9] which can cause Fermi-level pinning and high-leakage currents [5], and increased interface recombination [6, 7]. Progress might still be made through the use of appropriate oxidation barrier or spacer layers to distance the oxide from the channel [13]. However, the ultimate solution may be to eliminate As from the oxidized material altogether through the use of As-free phosphide-based III-V materials. In the last year of this project, we began exploring the electrical properties of the native oxide of $In_xAl_{1-x}P$, an alloy which is lattice matched to GaAs at composition x~0.5. While InAlP native oxides [7, 14-19] have received relatively little attention compared to those of AlGaAs, we have found them to be far superior in their insulating characteristics [18, 20, 21]. Specifically, leakage current densities are 3-4 orders of magnitude lower, and their dielectric strength is much higher, as discussed in section II below. Furthermore, we have observed the formation of an inversion layer in quasi-static capacitance-voltage (CV) measurements on several structures employing InAlP native oxides [20, 21]. To our knowledge, this is the first demonstration of its kind with any III-V native oxide, and suggests that the Fermi-level may be

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sufficiently unpinned for use in electronic device applications. If defect issues prove to be manageable, they promise ready compatibility with and significant benefits to existing high-electron-mobility transistor (HEMT) technology. They might also provide a means for effective surface passivation in other GaAs-based devices such as heterojunction bipolar transistors (HBTs) and metal-semiconductor-metal (MSM) photodiodes. The insulating quality of these InAlP native oxides appears competitive with the gadolinium-gallium oxides, $Ga_2O_3(Gd_2O_3)$, deposited in-situ from $Gd_3Ga_5O_{12}$, an approach developed over the past 5-6 years at Bell Laboratories/Lucent Technologies [22, 23]. Yet the native InAlP oxides, if proven viable, offer the advantage of greater device design and processing flexibility because of the possibility for selectively converting conducting semiconductor regions to the insulating oxide. Highlights of our research results under this award are presented below.

2. Summary of Major Research Activities and Findings

2.1 Current-Voltage (I-V) Measurements on III-V Native Oxides

We have recently reported [20, 21] our observation of significantly better electrical characteristics in wet-thermal native oxides of the As-free material, $In_{0.485}Al_{0.515}P$ (lattice-matched to GaAs). As shown in Table 1, leakage current densities for all the native oxides of InAlP are in the 10^{-10} A/cm^2 range (at 5 V), 3

Table 1: Average values for electrical data of studied structures after wet-thermal oxidation

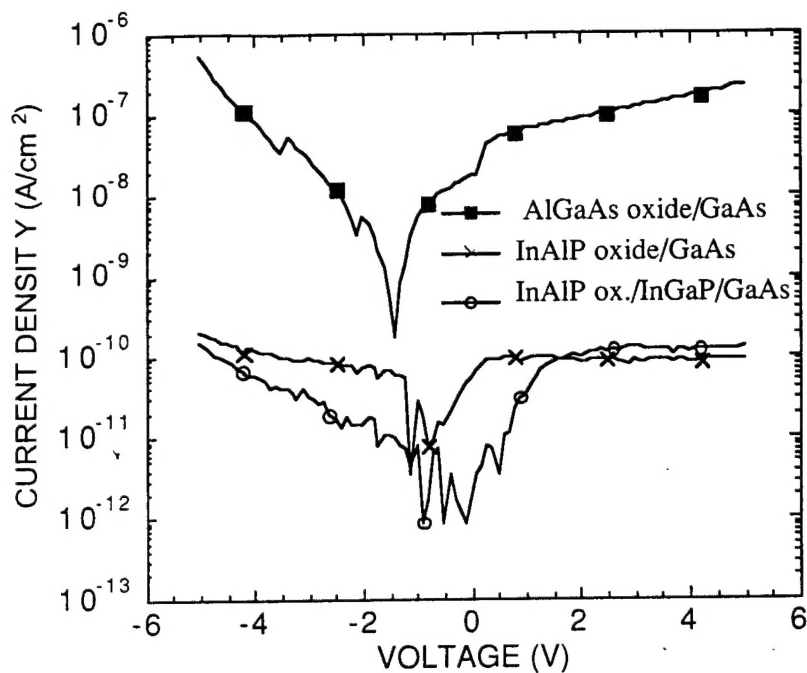| Structure Tested	$J_{Leakage}$ @ 5V (A/cm^2)	$E_{Breakdown}$ (MV/cm)	ε_r	D_{it} at midgap (10^{12}/cm^2/eV)
425 Al $_{0.98}$Ga$_{0.02}$As oxide	6.0e-6	3.75	4.66	2.3
1100 In $_{0.485}$Al$_{0.515}$P oxide	6.2e-10	6.35	6.57	1.1
1100 In $_{0.485}$Al$_{0.515}$P oxide/ 100 In $_{0.485}$Ga$_{0.515}$P	2.2e-10	6.33	5.77	1.3
Above, thinned to 490	7e-10	4.5	4.7	2

Figure 1. Typical IV curves for MOS capacitors (Area = 1.15×10^{-3} cm^2) with native oxides of AlGaAs or InAlP (with and without InGaP oxidation barrier).

to 4 orders of magnitude smaller than our average leakage result for surface-oxidized $Al_{0.98}Ga_{0.02}As$ films. Figure 1 shows typical current-voltage (IV) characteristics. Breakdown fields for InAlP native oxides are approximately 6 MV/cm -- about 1.5 times higher than average values for our AlGaAs oxides, and similar to those reported for $Ga_2O_3(Gd_2O_3)$ [23]. Typical breakdown curves are shown in Fig. 2. AlGaAs oxide breakdown strengths as high as 5.2 MV/cm (best result, as shown in Fig. 2) have been measured. The breakdown fields of InAlP oxides appear higher on average, and always with smoother and more symmetric curves than those seen with AlGaAs.

In these comparative studies of leakage current in AlGaAs vs. InAlP native oxides, we oxidized epitaxial films of approximately the same starting thickness. Because the AlGaAs contracts and the InAlP expands upon oxidation, the final oxide thicknesses were no longer comparable. Figure 3 shows data from 3 angle, single-wavelength ellipsometry measurements of the thickness of both the growing InAlP oxide and remaining unoxidized InAlP. The data shows qualitatively the non-linear, diffusion limited growth kinetics and indicates a volume expansion of ~2X when InAlP is oxidized.
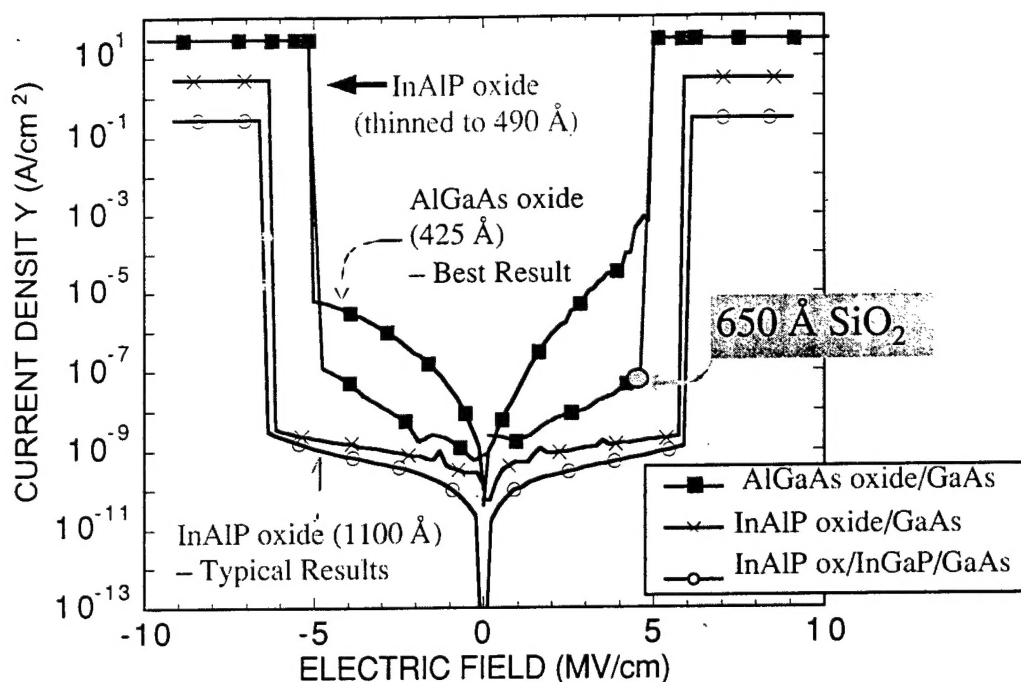
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Figure 2. Typical breakdown curves for MOS capacitors (Area = 3.6x10-5 cm2) with native oxides of 500 Å AlGaAs or 630 Å InAlP films (with and without InGaP oxidation barrier). The native oxide thicknesses are ~ 450 Å (AlGaAs) and ~1100 Å (InAlP). Average breakdown fields are given in Table 1.

From TEM measurements, we find that InAlP layers expand ~1.9X upon oxidation (e.g., from ~58 nm to ~110 nm). These values are consistent with studies from Prof. Dupuis' group at the U. of Texas at Austin [18]. Unlike AlGaAs, which contracts ~85% upon oxidation to a porous oxide from which most of the column V As escapes, this expansion indicates that very little In, Al
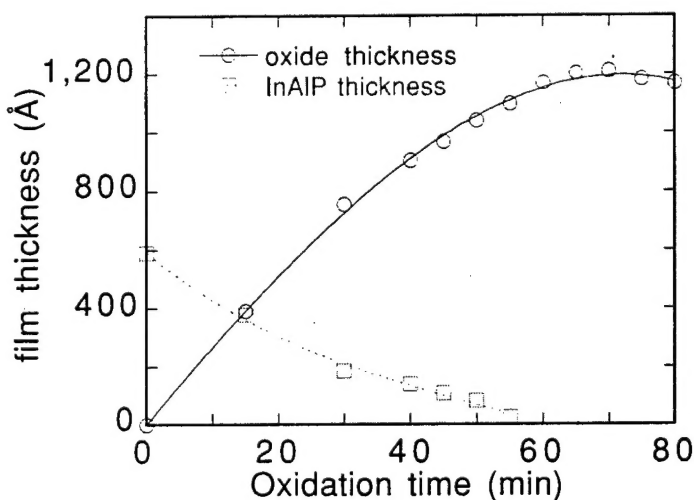

Figure 3. Single-wavelength (633 nm) ellipsometry of InAlP oxide and remaining InAlP thickness determined from data from two separate incidence angles. Data shows volume expansion upon oxidation and non-linear, diffusion-limited oxide growth.

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or P is desorbed from the InAlP during oxidation. Mathes et al. [17] have shown such films to contain Al_2O_3, In_2O_3, and P in some undetermined amorphous form. Using x-ray photoelectron spectroscopy (XPS), Dupuis' group has shown the InAlP native oxides to contain a large concentration of P_2O_5 [18], which contributes to their expansion and high density and may provide other beneficial properties. P_2O_5 is often added to SiO_2 to help getter sodium ions, and as a network former to make the glass more dense and resistant to the diffusion of these and other mobile ionic impurities.

Depending on the mechanism involved, it is possible that the leakage current might not scale linearly with film thickness, such that the InAlP oxides measured in Fig. 1 only appeared to be much better insulators because of their greater thickness. We performed controlled etch-back studies (removing oxide from the surface and measuring leakage for thinner films, as shown in Fig. 4) on two oxidized $In_{0.485}Al_{0.515}P$ films (with InGaP barrier layers) in which the starting 630 Å InAlP expanded to ~1100 Å after oxidation [21]. For a film thinned to 490 Å we found no significant increase in leakage (I~9e-14 A/

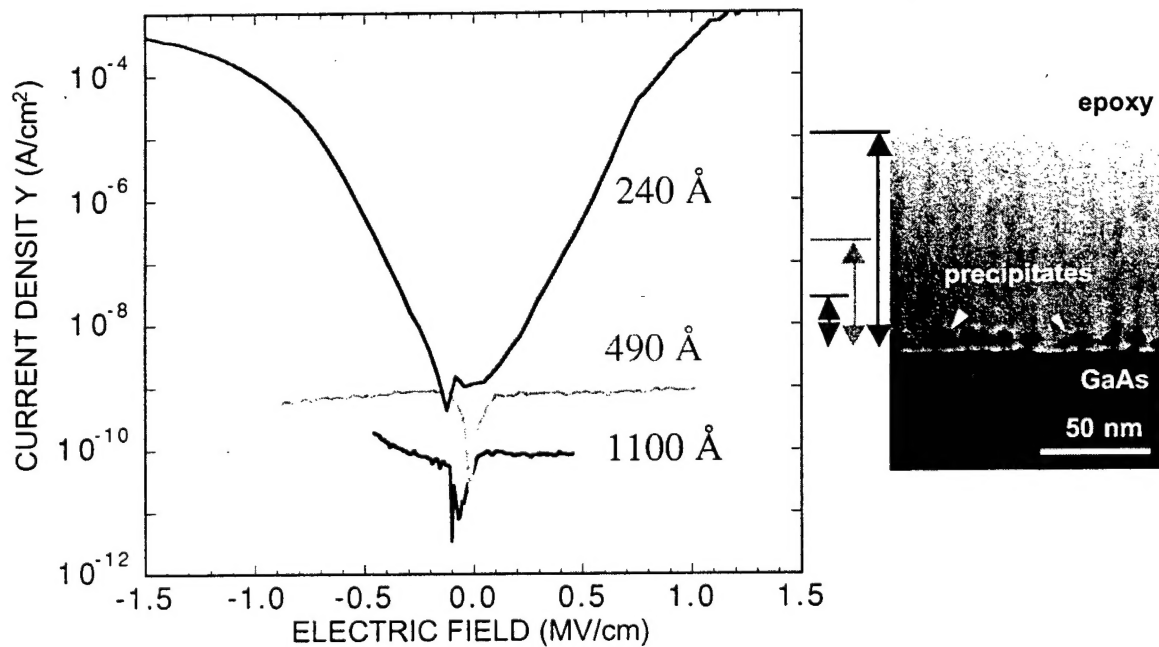Figure 4. Leakage current for InAlP oxide films at original thickness (1100 Å) and after thinning by etching back to 490 Å and 240 Å. The etch depth is indicated beside the TEM micrograph image at the right. The leakage current is seen to increase by only about 10X when thinned to a comparable thickness of the AlGaAs oxide of Fig. 2, but dramatically rises when etched into the region shown by the TEM image to contain precipitates.

14400 μm^2 @ 5V, or $J_L \sim$6.3e-10 A/cm^2). However, leakage was found to increase significantly when the film was etched to ~246 Å thickness (to I~2.3e-6 A/14400 μm^2 @ 5V, or $J_L \sim$1.6e-2 A/cm^2). Our TEM imaging, as seen in Fig. 4, shows that much of the remaining oxide in this last thin film is filled with higher density precipitates (darker contrast regions), which are clearly impacting the oxide quality. It is believed that these regions are In-containing compounds, as In is the heaviest element and most likely to cause increased electron scattering. From the lack of significant leakage increase in an oxide thinned to 490 Å, we can conclude that the clear oxide region above the precipitates *is* of good quality. We note that these were only two quick etch-back experiments and that no conclusions can be drawn from the ~3X higher leakage value for the 490 Å sample compared to average data of a larger sample set shown in Table 1. Further research is needed to understand the source and nature of the observed precipitate formation.

2.2 Capacitance-Voltage Measurements and Observation of Inversion

High-frequency (1 MHz) and low-frequency (quasi-static) capacitance-voltage (CV) measurements were performed on capacitors with areas ranging from 3600 to 115,200 μm^2. The quasi-static CV studies, useful for observation of inversion layer formation, have not been feasible in earlier investigations of AlGaAs or other III-V native oxides because of their high leakage currents [9]. With the much lower leakage levels obtained from the InAlP native oxides, quasi-static CV measurements are possible. Under dark-box measurement conditions, none of our InAlP oxide samples show evidence of an inversion layer. With electron-hole pair (EHP) generation via the illumination of a microscope lamp, many of our InAlP oxide samples show clear signs of an inversion layer, characteristic of a relatively clean interface and possibly unpinned Fermi level. Figure 5 shows a strong reverse bias increase in capacitance (corresponding to hole accumulation and inversion layer formation) for one such InAlP/GaAs sample oxidized for 60 min at 500 °C. The apparent inversion layer formation is dependent on oxidation time, t_{ox}. For full oxidation, near t_{ox}=60 min, the inversion effect is the strongest. At t_{ox}=90 min, the degree of inversion is reduced and, at t_{ox}=120 min, the inversion layer does not develop at all, which we attribute to excessive over-

oxidation into the GaAs substrate. Samples containing a 10 nm InGaP oxidation barrier layer below the InAlP exhibit similar behavior, but with less reduction of inversion at t_{ox}=90 min than observed in samples without the barrier. High frequency CV measurements [20, 21] are consistent with quasi-static behavior, as a flat inversion region forms with illumination for samples oxidized for 60 min, again suggesting the presence of an inversion layer. For other times, sloping inversion regions indicate varying degrees of deep depletion. The need for optical generation of electron-hole pairs does not itself necessarily imply the presence of traps, as the thermal generation rates are quite low here due to the larger energy gap of GaAs. It is not uncommon in other wide-bandgap systems (e.g., in GaN MOS research) [24] to require light for carrier generation. The dashed curves of Fig. 5 shows that leakage (Q/t data) measured during the quasi-static CV scan is negligibly small, indicating that thermal equilibrium is maintained throughout the measurement.
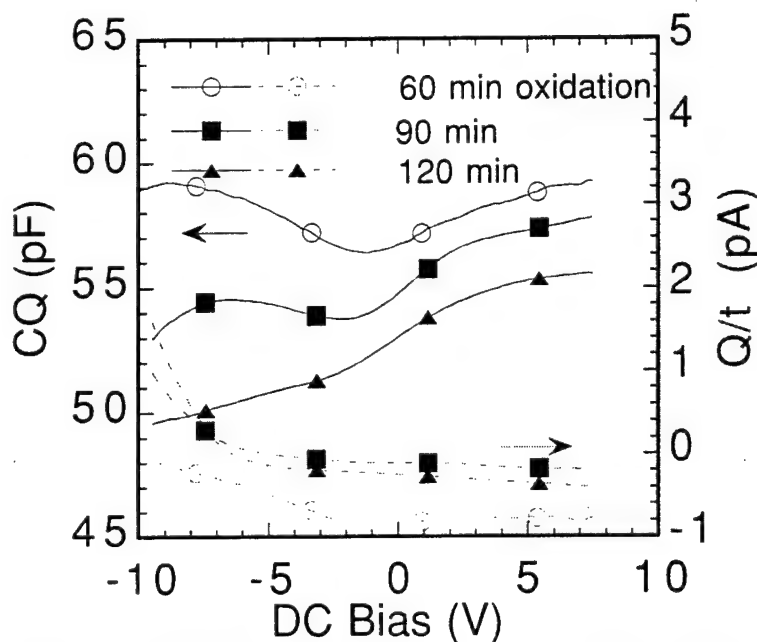

Figure 5. Low-frequency (quasi-static, "CQ") C-V curves of InAlP/InGaP MOS devices surface oxidized at 500°C for 60, 90 or 120 min. Dashed curves show low dc leakage (Q/t). Increasing capacitance C for increasingly negative V indicates formation of inversion layer (accumulation of holes).

2.3 Transmission Electron Microscopy (TEM) Results

Transmission electron microscopy (TEM) studies at both Notre Dame and Lawrence Berkeley National Laboratory (LBNL) were performed on samples oxidized (60 min, 500 °C) with those showing inversion behavior to determine where the inversion layer is occurring within the oxidized InAlP/GaAs or InAlP/InGaP/GaAs heterostructures [20, 21]. The Notre Dame TEM image of Fig. 6 shows an amorphous oxide above a darker contrast, crystalline layer (the InGaP barrier). The InGaP/GaAs interface remains uniform and epitaxial. These measurements indicate thicknesses of ~1100 Å for the InAlP native oxide and 100 Å
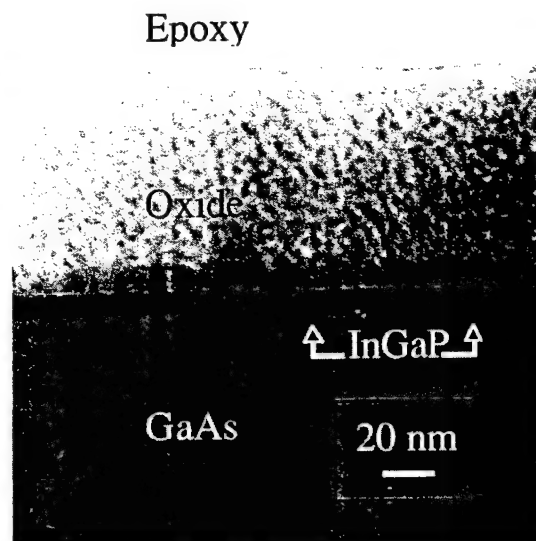

Figure 6. Bright-field TEM image of an oxidized InAlP/InGaP/GaAs sample showing 100 Å InGaP barrier and darker region of precipitates just above it. (Courtesy of Prof. T. H. Kosel, University of Notre Dame)

(matching the as-grown thickness) for the InGaP buried layer. This suggests a high oxidation rate selectivity between InAlP and InGaP such that the latter effectively stops the progressing oxidation front. A darker contrast region just above the oxide/InGaP interface is thought to be due to denser materials in the form of In or InP. These precipitates were observed in earlier work by Mathes et al. [17], and are seen in TEM images from LBNL (Fig. 7(b)) as well. Fig. 7 shows TEM images of a similar sample to that of Fig. 6 for (a) the unoxidized, as-grown structure with InGaP barrier layer and (b) after oxidation, where a region of dark precipates near the interface is again observed. This precipitated interface region is most likely not a suitable host for an inversion layer due to the large amount of disordering and interface states that these byproducts could introduce. On the other hand, the InGaP/GaAs interface is quite clean and smooth and can likely be readily inverted as revealed by our CV measurements.

The InGaP barrier layer does not obviously affect the formation of these precipates, but was shown in Sec. 2.1 to improve the oxide's electrical properties, and is also shown here to be effective in yielding
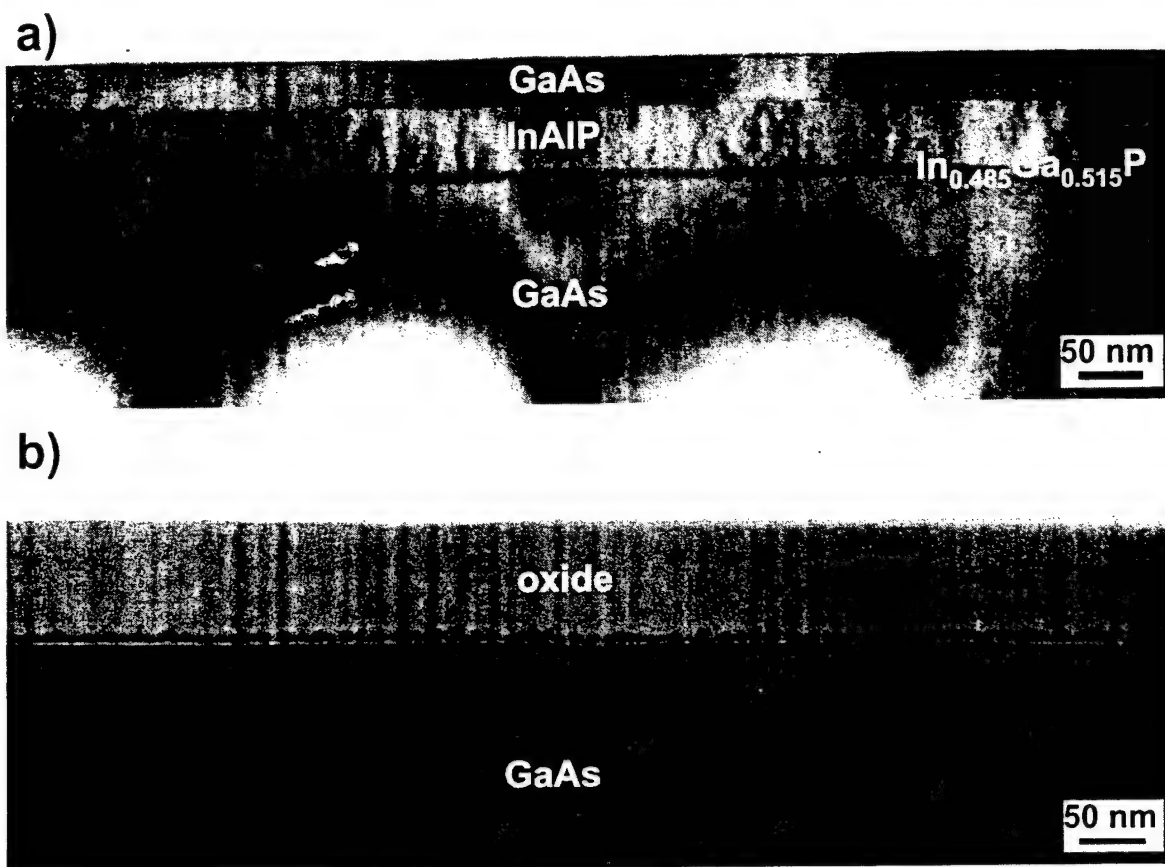
Figure 7. TEM image of an GaAs/InAlP/InGaP/GaAs sample shown (a) as grown and (b) after oxidation, showing darker region of precipitates just above 100 Å InGaP barrier layer. (Courtesy of J. B. Jasinski and Z. Liliental-Weber, Lawrence Berkeley National Laboratory)

oxides with greater thickness uniformity. Figure 8 shows a larger portion of the image seen in Fig. 4. It is

clear that without the InGaP oxidation barrier layer, the thickness uniformity is much worse than seen with

the barrier in Fig. 7(b). The oxide thickness in Fig. 8 is ~1025 Å with thickness fluctuations of ~50 Å.

Figure 9 shows a high resolution TEM image of the sample with the InGaP barrier (Fig. 7 (b)), from which

it can be seen that the oxidation front has been effectively stopped by the InGaP oxidation barrier layer.

Again, it is most likely in these samples that the inversion layer forms at the clean InGaP/GaAs

heterointerface. Figure 10 (a) shows a higher magnification TEM image of the sample with no InGaP

barrier of Fig. 8, with a high-resolution image of the interface shown in Fig. 10(b). These images show that

the crystalline InAlP/GaAs interface also was preserved for the 60 min oxidation time, providing a clean
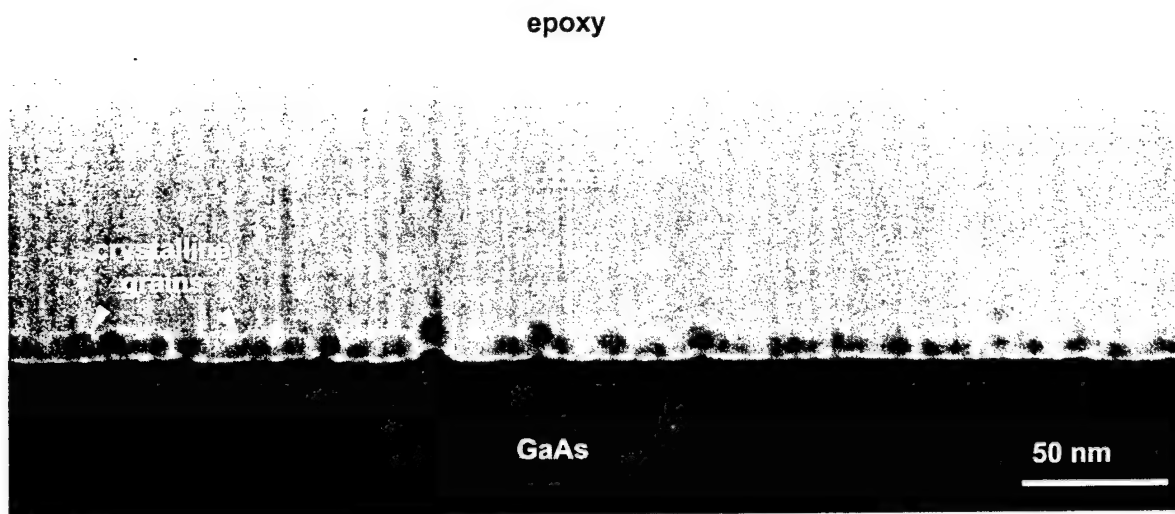
epoxy

Figure 8. Larger view of TEM image from Fig. 4 of an oxidized InAlP sample with no barrier layer. A darker region of precipitates identified as crystalline grains is seen near the oxide/semiconductor interface, and in contrast to the sample with an InGaP barrier layer (Fig. 7), the oxide shows thickness fluctuates of ~50Å. (Courtesy of J. B. Jasinski and Z. Liliental-Weber, Lawrence Berkeley National Laboratory)

semiconductor/semiconductor heterointerface at which the inversion layer likely forms in these samples. The oxidation front has surprisingly halted just before the GaAs, even without an intentional barrier layer. We have observed with other ellipsometric and capacitance measurements that for oxidation times beyond 60 min there is no obvious increase in oxide thickness, supporting the notion that the oxidation process was not simply stopped coincidentally when the oxidation front was within a few monolayers of the GaAs. What is particularly remarkable, then, is that the oxidation of the GaAs has apparently been prevented or suppressed, even though unprotected GaAs oxidizes relatively quickly at these temperatures. We have found in other experiments that, in marked contrast, AlGaAs native oxides do not prevent oxidation of underlying GaAs. This is because AlGaAs wet oxidation results in porous oxides (with a reaction-rate-limited, linear growth dependence with time). The InAlP oxide, however, must be quite dense in order to prevent the outdiffusion of Ga and As, as necessary for GaAs oxidation. This is consistent with the observed diffusion-limited oxidation kinetics of InAlP (decreasing growth rate vs. time, as shown in Fig. 3). InAlP native oxides may thus have tremendous value to GaAs as a protective capping layer to reduce or prevent dissociation during high-temperature processing.
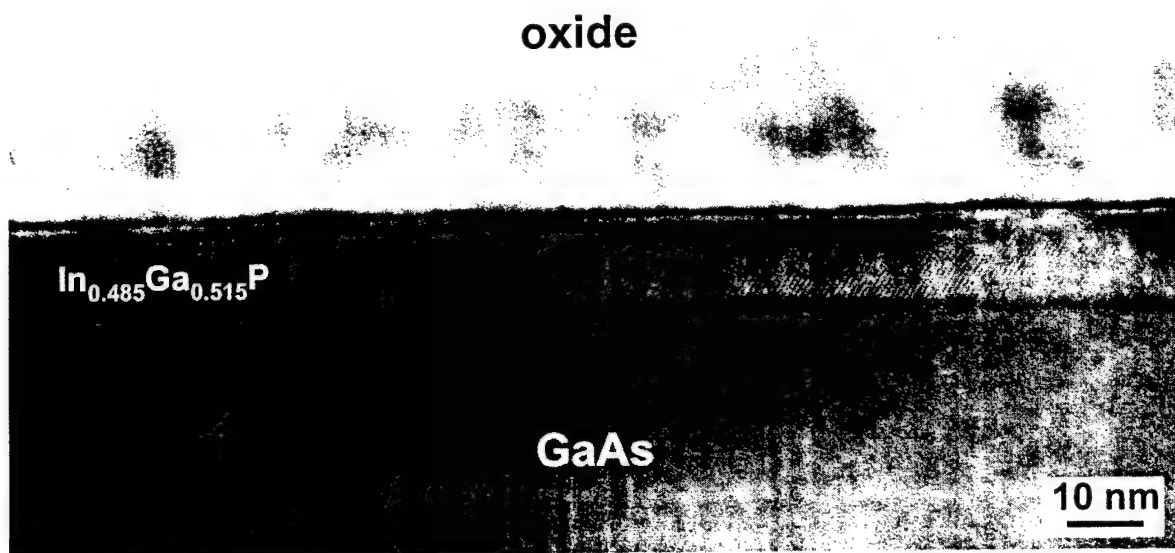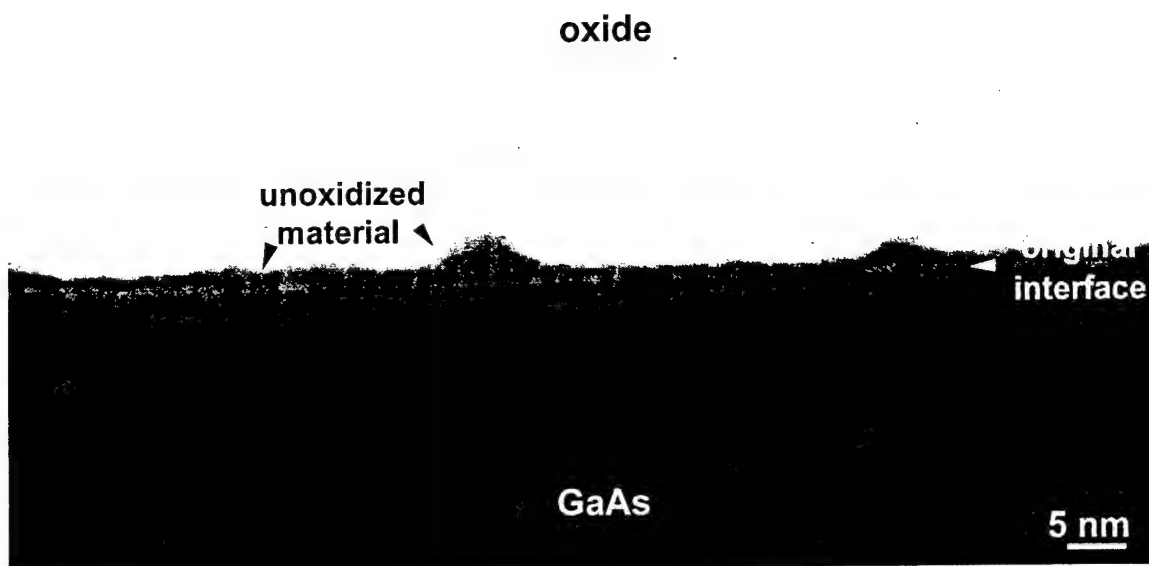
Figure 9. High resolution TEM image of InAlP oxide/InGaP/GaAs interface region for sample shown in Fig. 7(b). (Courtesy of J. B. Jasinski and Z. Liliental-Weber, Lawrence Berkeley National Laboratory)

For TEM analysis of our samples, we have collaborated with Dr. Zuzanna Liliental-Weber and her postdoctoral associate Dr. Jacek Jasinski at Lawrence Berkeley National Laboratory. TEM analysis of semiconductor and oxide films on GaAs substrates has also recently been made possible at Notre Dame through development (by Prof. Thomas H. Kosel) of a TEM specimen preparation technique using a novel wedge-polishing apparatus combined with a Technoorg-Linda low-energy ion milling system. Cross sectional TEM specimens are routinely prepared with nearly 100% success rate, normally by wedge polishing to a thickness of about 2 μm followed by Ar ion milling at 2 keV or less. It has been shown that specimens of the native oxides on GaAs can be thinned to final electron transparency by wedge polishing alone, eliminating the possibility of ion damage. Furthermore, the low-energy ion gun can be operated at energies as low as 200 eV, greatly reducing ion damage during thinning.

(a)

oxide

unoxidized
material

original
interface

GaAs

5 nm

(b)

oxide

unoxidized
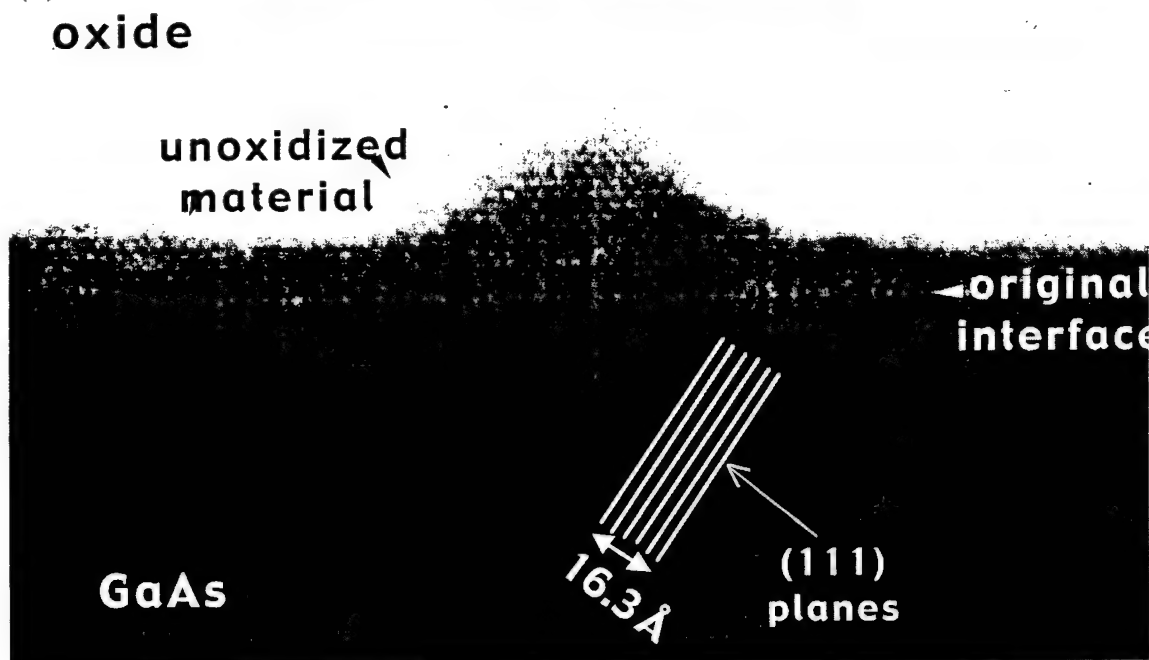material

original
interface

GaAs

16.3 Å

(111)
planes

Figure 10. Two higher resolution TEM images of the InAlP oxide interface region for the sample of Fig. 9. Images clearly show the original InAlP/GaAs heterointerface is preserved. In (b), the crystal lattice of the unoxidized InAlP and GaAs can be seen.(Courtesy of J. B. Jasinski and Z. Liliental-Weber, Lawrence Berkeley National Laboratory)

The wedge-polished specimen geometry has the advantage of providing a very long, straight thin edge of nearly uniform thickness, which permits examination of much larger specimen areas than the more conventional dimple-polished specimen geometry. Specimens are examined in the JEOL 100C TEM in the Notre Dame Department of Electrical Engineering (used for the image in Fig. 6). In the last months of this project, a successful collaboration has also been set up with the Electron Microscopy Center at Argonne National Laboratory.

2.4 X-ray Characterization Results

We performed extensive x-ray absorption fine-structure spectroscopy (XAFS) and x-ray reflectivity studies of III-V compound semiconductor native oxide films at the Advanced Photon Source at Argonne National Laboratory [25-30]. We have identified the residual As site in an oxidized ~0.5 μm $Al_{0.96}Ga_{0.04}As$ film [30]. In a ~0.5 μm oxide film removed from its GaAs substrate, the remaining As atoms were found to be coordinated with oxygen in the form of amorphous As oxides, with a mixture of ~80% As^{3+} and ~20% As^{5+} sites that are locally similar to As_2O_3 and As_2O_5. No evidence of interstitial or substitutional As, As precipitates or GaAs was seen, implying that less than 10% of the As atoms are in these forms.

We have also achieved success in obtaining and interpreting very high quality (large dynamic range) reflectivity data, such as that shown below in Fig. 11 [26-29]. This past year we have implemented a powerful model-independent fitting method based on the Distorted Wave Born Approximation (DWBA) [28]. The resulting best fit from this model-independent method is shown in Figure 11 as a solid line through the data. The resulting density profile in Figure 12 shows that there is a high density layer (~30 Å) at the surface with a density very close to that of GaAs. We originally attributed the presence of a thin higher density GaAs surface layer to a residue of the original 500 Å GaAs protective cap not fully removed by a citric acid/hydrogen peroxide selective etch before oxidation. However, the sample measured here was subjected to an additional 4 sec in a non-selective sulfuric peroxide etch that should have fully

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removed the GaAs as well as some of the AlGaAs film. Furthermore, any residual GaAs should have been oxidized. The presence of Ga at the surface was confirmed by both reflection-mode XAFS and X-ray photo-electron spectroscopy (XPS). We believe the higher density Ga-rich surface layer may be the result of Ga and As outdiffusion through the porous oxide film. Such outdiffusion has been shown to be the mechanism by which growth of thermal oxides of GaAs proceeds outward. A low-density layer (~60 Å) overlying a higher density oxide layer (170 Å) is possibly due to the formation of lower density hydroxides near the surface during the initial stages of surface oxidation. These results demonstrate the powerful capability of x-ray analysis to determine with high resolution the atomic nature and morphology of thin oxide films.
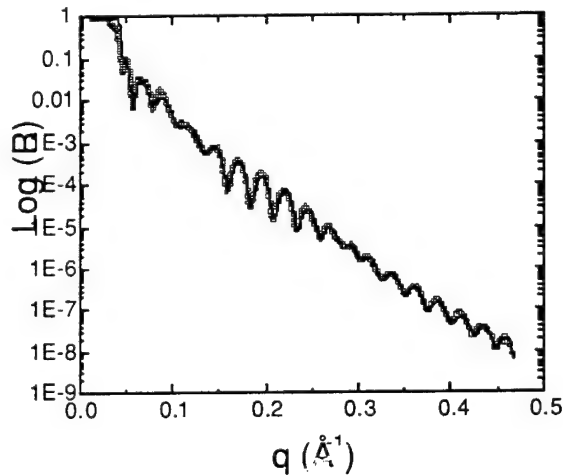

Figure 11. The measured x-ray reflectivity data of an oxidized 300 Å $Al_{0.94}Ga_{0.06}As$ film on GaAs with best fit using a model-independent methods.
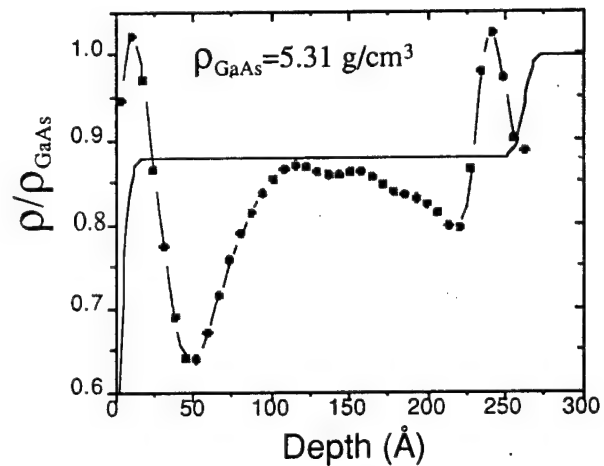
Figure 12. Calculated density profile from the model-independent fit of Fig. 11 (red line with symbol) and model-dependent fit for single-layer with surface and interface roughness (black solid line).

2.5 Oxidation Barrier Layers and Interface Traps

An important issue for utilizing these new III-V native oxides in device applications is their integration into the heterostructures upon which advanced electronic devices are based. The primary issue here is expanding our knowledge of the differences in oxidation and etch rates of the various materials at our disposal. In particular, it is necessary to find suitable oxidation barrier layers to prevent overoxidation into underlying heterolayers while yielding smooth and defect free interface regions. Part of our earliest efforts were focused on comparative studies of AlGaAs native oxide samples with and without an InGaP oxidation barrier layer [13]. Samples containing an oxidation barrier show a one order of magnitude decrease in leakage when oxidized laterally. The barrier layer also apparently slows or prevents the reactions with the GaAs underlayer that create additional bulk and interfacial residual As and increased

$$J_{Leakage} \text{ @ } 5 \text{ } V \text{ for } 500 \text{ Å } Al_{0.98}Ga_{0.02}As \text{ oxidation layer}$$

Surface Oxidation Conditions: 430 °C, 5 min

Lateral Oxidation Conditions: 430 °C, 25 min
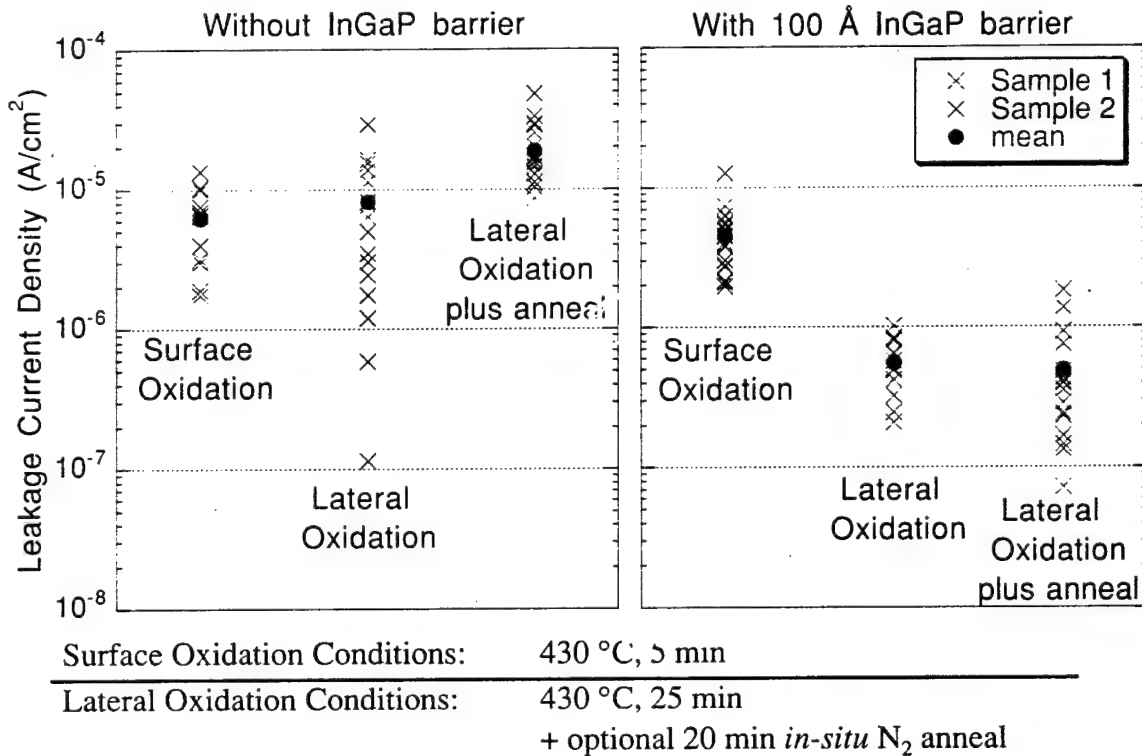+ optional 20 min *in-situ* N_2 anneal

Fig. 13. Leakage current density for oxidized 500 Å $Al_{0.98}Ga_{0.02}As$ layer with (right) and without (left) InGaP barrier layer for different process conditions. The leakage current density is seen to be reduced by more than one order of magnitude for samples with the InGaP barrier layer, suggesting a reduction in residual As in the films..

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leakage. The prevented reaction may be the direct oxidation of GaAs or the reaction of GaAs with As_2O_3 found at the oxidation front, $2GaAs + As_2O_3 \rightarrow 4As + Ga_2O_3$. C-V measurements indicate that, compared to samples with no barrier ($\varepsilon=4.0\varepsilon_0$, $D_{it}=2.3\times10^{12}/cm^2/eV$), an improved dielectric layer ($\varepsilon=5.4\varepsilon_0$) with a reduced interfacial trap density ($D_{it}=7\times10^{11}/cm^2/eV$) is obtained for the sample with the InGaP oxidation barrier. For samples having an oxidation barrier, we have also found that a 20 min. in-situ N_2 anneal results in a decrease in interface trap density. This is likely due to the prevention of the $2GaAs + As_2O_3 \rightarrow 4As + Ga_2O_3$ reaction, reducing the quantity of interfacial As. We have also observed low hysteresis in the CV measurements, characteristic of high quality films. These results show that it is possible to reduce not only leakage in the oxides but also interface densities with the proper choice of materials and oxidation conditions, bringing us closer to the realizing a III-V MOS transistor technology which promises faster, low-power-dissipation transistors.

In order for the InAlP native oxides to be fully assessed for their applicability to advanced electronics devices, their charge trapping properties must be evaluated. Metal-Oxide-Semiconductor (MOS) field-effect devices rely for their operation on the ability to controllably modulate the charge in a conducting channel, and undesirable fixed and mobile charges in the oxide bulk and fast interface charge traps can seriously limit device performance. One consequence of a large density of midgap traps is "pinning" of the Fermi level, preventing modulation of channel charge. Our observation (in Fig. 5) of modulating the n-type channel charge from accumulation of electrons under positive bias to accumulation of holes under negative bias (i.e. *inversion* of material to "p-type") indicates the trap level is sufficiently low to avoid severe Fermi-level pinning. However, high-frequency C-V data [20, 23] does show symptoms indicating the presence of traps. The density of these traps and their impact on device performance has yet to be characterized. We recall here that time-resolved PL studies have shown remarkable differences in the luminescence properties of GaAs layers capped by $In_{0.485}Al_{0.515}P$ and $Al_{0.9}Ga_{0.1}As$ native oxides, with the former showing a marked increase in the luminescence efficiency and decay time, and the latter a dramatic decrease in these quantities [7, 15, 16, 19]. This data originally inspired our further study of the As-free

oxides, and still suggests that the trapping behavior of residual P defects is less detrimental than that of residual As defects.

In this project, we have fabricated standard MOS capacitor devices with InAlP oxides and measured their high-frequency (1 MHz) and quasi-static capacitance-voltage (C-V) characteristics with our Keithley Model 82 C-V measurement system. Doping levels of the semiconductor were not optimal for C-V characterization, limiting our ability to extract meaningful information about trap densities. Samples with more appropriate doping would give greater C-V modulation and more sensitivity to traps and enable us to gain additional insight into the quality of these native oxides with now routine C-V characterization.

Deep Level Transient Spectroscopy (DLTS) measurements study the transient capacitance response and its temperature dependence. Analysis of DLTS data provides the most accurate information about the density and energy location of traps. Our first DLTS system was found to have deficiencies limiting our ability to perform the required measurements. Towards the end of the project, we acquired a complete Sula Technologies DLTS system and cryostat on extended loan from Prof. Jacek Furdyna (Dept. of Physics, Univ. of Notre Dame). The equipment is state-of-the-art and has the capability for several variations on DLTS, including constant capacitance (CC-) DLTS. Progress was made in upgrading the sample fixturing and developing new computer control programs through the efforts of an Electrical Engineering undergraduate student making the effort his senior design research project.

2.6 MOSFET Devices Employing Compound Semiconductor Native Oxides

For applications in high-speed, low-power signal processing and high-speed, high-efficiency amplification, the unique material properties of III-V native oxides promise significant advantages for realizing high-performance MOSFET devices. Of particular promise is the insulated-gate buried-channel high-electron-mobility transistor (HEMT). In this device, the Schottky barrier layer of a conventional HEMT is replaced by a layer of III-V native oxide (hence, "insulated gate"). The spacer layer between the channel and this oxide layer is maintained, e.g. InAlP or InGaP, and a pseudomorphic $In_{0.2}Ga_{0.8}As$

channel as in conventional devices is maintained. If a low trap density can be achieved in the oxide and at the oxide-semiconductor interface, such a device would have several important advantages over conventional HEMT devices. Such devices could significantly outperform present Si and GaAs electronics due to the lower effective mass and corresponding higher electron mobilities and saturation velocities in the channel.

In a conventional HEMT, the gate voltage can swing at most from threshold to approximately the gate Schottky barrier height while still modulating the drain current. Voltages below the threshold voltage place the device in cutoff, while gate voltages in excess of the Schottky barrier height forward bias the gate and result in current saturation and transconductance compression. In the insulated-gate HEMT, the much higher gate voltage possible allows a greatly increased carrier concentration beneath the gate and, thus, increased drain current well beyond the limitations of Schottky-gated devices. III-V MOSFETs can thus offer a much greater noise margin by reducing the gate leakage current while retaining the advantages of a high-mobility channel. Current saturation effects are pushed out to more positive gate voltages and larger voltage swings can be accommodated. In this research effort, progress was made towards bringing a viable gate oxide for GaAs-based MOSFET devices closer to a reality. We demonstrated a depletion-mode (normally on) GaAs-based high-electron-mobility (pseudomorphic InGaAs channel) MOSFET (or insulated-gate HEMT) device using the AlGaAs native oxide [4]. Limited material with appropriate doping for such MOSFET devices prevented more complete characterization of device possibilities and performance.

3. Project Participants

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4. Publications

The following papers (with reference numbers as cited in this report) resulted from this research effort.

1. C. B. DeMelo, D. C. Hall, G. L. Snider, D. Xu, G. Kramer, and N. El-Zein, "High-Electron-Mobility InGaAs-GaAs Field-Effect Transistor with Thermally Oxidized AlAs Gate Insulator," *Electron. Lett.*, vol. 36, pp. 84-86, 2000. [Ref. 4]

2. Pedro J. Barrios, Seong-Kyun Cheong, Douglas C. Hall, Nathaniel C. Crain, Gregory L. Snider, Christine B. DeMelo, Tomohiro Shibata, Bruce A. Bunker, Uttiya Chowdhury, Russell D. Dupuis, Gary Kramer, and Nada El-Zein, "Residual As and the Electrical Characteristics of AlGaAs Native Oxides for MOS Applications," *42nd Electronic Materials Conference*, paper F3 (Denver, Colorado, June 21-23, 2000). [Ref. 13]

3. Pedro J. Barrios, Douglas C. Hall, Gregory L. Snider, Thomas H. Kosel, Uttiya Chowdhury and Russell D. Dupuis, "Electrical properties of InAlP native oxides for GaAs-based MOS applications," *Thirty-Fourth State-of-the-Art Program on Compound Semiconductors (SOTAPOCS XXXIV)* at the *199th Meeting of the Electrochemical Society* (Washington, D.C., March 25-30, 2001); published in *The Electrochemical Society Proceedings*, vol. 2001-1, edited by F. Ren, D. N. Buckley, S. N. G. Chu and S. J. Pearton, pp. 258-264 (2001). [Ref. 20]

4. P. J. Barrios, D. C. Hall, U. Chowdhury, R. D. Dupuis, J. B. Jasinski, Z. Liliental-Weber, T. H. Kosel, and G. L. Snider, "Properties of InAlP Native Oxides Supporting MOS Inversion-layer Behavior," 43rd Electronic Materials Conference, paper DD4 (Notre Dame, Indiana, June 27-29, 2001). [Ref. 21]

5. Seong-Kyun Cheong, Tomohiro Shibata, Maxim Boyanov, Debdutta Lahiri, Bruce A. Bunker, Douglas C. Hall, Gregory L. Snider and Christine B. DeMelo, "Reflection Mode XAFS studies of III-V compound native oxide/GaAs Interfaces," American Physical Society 1999 Centennial Meeting, paper XC23.09 (Atlanta, Georgia, March 20-26, 1999). [Ref. 25]

6. Seong-kyun Cheong, Tomohiro Shibata, Maxim Boyanov, Debdutta Lahiri, Bruce A. Bunker, Douglas C. Hall, and Gregory L. Snider, "X-ray reflectivity and reflection-mode XAFS study of III-V compound native oxide/GaAs interfaces," 2000 March Meeting of American Physical Society, paper I19.02 (Minneapolis, Minnesota, March 20-24, 2000). [Ref. 26]

7. Bruce A. Bunker, Seong-kyun Cheong, Tomohiro Shibata, Maxim Boyanov, Debdutta Lahiri, Douglas C. Hall, Gregory L. Snider and Pedro J. Barrios, "Reflectivity and Reflection-mode XAFS study of Ill-V compound native oxide/GaAs Interface", 11th International Conference on X-ray Absorption Fine Structure (XAFS XI), paper B6-04 (Ako, Japan, July 27-31, 2000). [Ref. 27]

8. Seong-Kyun Cheong, Bruce A. Bunker, D.C. Hall, G.L. Snider, and P. J. Barrios, XAFS and X-ray reflectivity study of III-V compound semiconductor native oxide/GaAs interfaces," Journal of Synchrotron Radiation, vol. 8, pp. 824-826 (2001). [Ref. 28]

9. Seong-Kyun Cheong, Tomohiro Shibata, Maxim Boyanov, Debdutta Lahiri, Bruce A. Bunker, Douglas C. Hall, Gregory L. Snider and Pedro J. Barrios, "Reflectivity and Reflection-mode XAFS study of the wet-thermal native oxide/GaAs interface," 2001 March Meeting of American Physical Society, paper J11.010 (Seattle, Washington, March 12-16, 2001), published in the Bulletin of the Americal Physical Society, vol. 46, no. 1 (2001). [Ref. 29]

10. S.-K. Cheong, B. A. Bunker, T. Shibata, D. C. Hall, C. B. DeMelo, Y. Luo, G. L. Snider, G. Kramer, and N. El-Zein, "The residual arsenic site in oxidized $Al_xGa_{1-x}As$ (x=0.96)," *Appl. Phys. Lett.*, vol. 78, pp. 2458-2460 (2001). [Ref. 30]

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